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INTERNATIONAL STANDARD

NORME INTERNATIONALE

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Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (frequency range of 6 GHz to 300 GHz) – Part 1: Measurement procedure

Évaluation de la densité de puissance de l'exposition humaine aux champs radiofréquences provenant de dispositifs sans fil à proximité immédiate de la tête et du corps (plage de fréquences de 6 GHz à 300 GHz) – Partie 1: Procédure de mesure

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue
New York, NY 10016-5997
United States of America
stds.ipr@ieee.org
www.ieee.org

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ASSESSMENT OF POWER DENSITY OF HUMAN EXPOSURE TO RADIO FREQUENCY FIELDS FROM WIRELESS DEVICES IN CLOSE PROXIMITY TO THE HEAD AND BODY (FREQUENCY RANGE OF 6 GHz TO 300 GHz) –

Part 1: Measurement procedure

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This document is published as an IEC/IEEE Dual Logo standard.

This publication contains supplemental files in the form of analytical reference functions for validation of the reconstruction algorithms in Annex E. Download links for these files can be found in Clause E.5.

The text of this International Standard is based on the following IEC documents:

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INTRODUCTION

This document provides methods to evaluate incident power density exposures due to any electromagnetic field (EMF) transmitting device intended to be used at a position near the human head or body, or mounted on the body, combined with other transmitters within a product, or embedded in garments. The device categories covered include but are not limited to mobile telephones, radio transmitters in personal computers, and desktop and laptop devices. This document also addresses multi-band and multi-antenna devices. The overall applicable frequency range is from 6 GHz to 300 GHz. This document specifies:

- measurement system (Clause 6);
- power density measurement protocols (Clause 7);
- uncertainty evaluation (Clause 8);
- measurement report (Clause 9);
- system checks and system validation (Annex B).

To develop this document, IEC Technical Committee 106 (TC 106) and Technical Committee 34 (TC 34) Subcommittee 1 (SC 1) of IEEE International Committee on Electromagnetic Safety (ICES) formed Joint Working Group 12 (JWG 12) on measurement methods to assess the power density of electromagnetic fields from wireless devices in close proximity to the head and body.

This document is partly based on IEC TR 63170:2018.

NOTE System validation tests are specified in Annex B for 10 GHz, 30 GHz, 60 GHz, and 90 GHz to cover the frequency range from 6 GHz to 110 GHz. Additional validation antennas to cover the frequency range up to 300 GHz will be developed in a future revision of this document. Further discussion on rationales is given in Annex I.

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ASSESSMENT OF POWER DENSITY OF HUMAN EXPOSURE TO RADIO FREQUENCY FIELDS FROM WIRELESS DEVICES IN CLOSE PROXIMITY TO THE HEAD AND BODY (FREQUENCY RANGE OF 6 GHz TO 300 GHz) –

Part 1: Measurement procedure

1 Scope

This document specifies protocols and test procedures for repeatable and reproducible measurements of power density (PD) that provide conservative estimates of exposure incident to a human head or body due to radio-frequency (RF) electromagnetic field (EMF) transmitting communication devices, with a specified measurement uncertainty. These protocols and procedures apply for exposure evaluations of a significant majority of the population during the use of hand-held and body-worn RF transmitting communication devices. The methods apply for devices that can feature single or multiple transmitters or antennas, and can be operated with their radiating structure(s) at distances up to 200 mm from a human head or body.

The methods of this document can be used to determine conformity with applicable maximum PD requirements of different types of RF transmitting communication devices being used in close proximity to the head and body, including if combined with other RF transmitting or non-transmitting devices or accessories (e.g. belt-clip), or embedded in garments. The overall applicable frequency range of these protocols and procedures is from 6 GHz to 300 GHz.

The RF transmitting communication device categories covered in this document include but are not limited to mobile telephones, radio transmitters in personal computers, desktop and laptop devices, and multi-band and multi-antenna devices.

NOTE 1 System validation tests are specified in Annex B for 10 GHz, 30 GHz, 60 GHz, and 90 GHz to cover the frequency range from 6 GHz to 110 GHz. Additional validation antennas to cover the frequency range up to 300 GHz will be developed in a future revision of this document. Further discussion on rationales is given in Annex I.

NOTE 2 The protocols and test procedures in this document can be adapted to evaluate exposure also due to non-communication types of devices operating in close proximity to the head and body, but these devices are not in the scope of this document.

NOTE 3 For the assessment of the combined exposure from simultaneous transmitters operating on frequencies below 6 GHz, the relevant standards for SAR measurements are IEC/IEEE 62209-1528:2020 and IEC/IEEE 62209-3:2019 [1].

NOTE 4 Between 6 GHz and 10 GHz, the scopes of this document and IEC/IEEE 62209-1528:2020 overlap. According to ICNIRP [2] guidelines and IEEE ICES C95.1 [3] standard, power density is the conformity metric in this frequency range. SAR can be used as conformity metric if local regulatory requirements allow it. (e.g. in case where a single transmit band includes test channels at both below and above 6 GHz).

The procedures of this document do not apply for EMF measurements of devices or objects intended to be implanted in the body.

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2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/IEEE 62209-1528:2020, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Part 1528: Human models, instrumentation, and procedures (Frequency range of 4 MHz to 10 GHz)*

IEC/IEEE 63195-2:2021[1], *Assessment of power density of human exposure to radio frequency fields from wireless devices in close proximity to the head and body (Frequency range of 6 GHz to 300 GHz) – Part 2: Computational procedure*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO, IEC, and IEEE maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp
- IEEE Dictionary Online: available at http://dictionary.ieee.org

3.1 Exposure metrics and parameters

3.1.1
power density
PD
local power density
function of the complex Poynting vector $\boldsymbol{S}$ at the location $\boldsymbol{r}$ that is integrated over a surface to calculate the sPD

Note 1 to entry: Specifications of power density in terms of the integrands of Formula (4), Formula (5), and Formula (8) are provided in 6.7.1. See also rationales provided in Annex I for the PD specifications of 6.7.1.

Note 2 to entry: The formula used to calculate PD can depend on the applicable exposure guidelines or national regulations.

Note 3 to entry: Power density is also referred to as power flux density.

Note 4 to entry: The associated term incident power density refers to quantity of power per unit area that impinges on the body surface. The incident power density just outside the body surface is used to establish local exposure reference levels, which apply at frequencies above 6 GHz in some jurisdictions.

3.1.2
spatial-average power density
sPD
PD (3.1.1) averaged over a surface of area A_{av}

Note 1 to entry: sPD is a function of the location vector $\boldsymbol{r}$. It is defined on the evaluation surface, except for the edges where no averaging area can be constructed.

Note 2 to entry: Example averaging area sizes specified in exposure limits are 1 cm^2 and/or 4 cm^2.

[1] To be published.

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3.1.3
peak spatial-average power density
psPD
global maximum value of all *sPD* (3.1.2) values on the evaluation surface (3.2.3)

Note 1 to entry: *psPD* is given by Formula (1)

$$psPD = \max_{\boldsymbol{r}} \left\{ sPD(\boldsymbol{r}) \right\} \tag{1}$$

where $\boldsymbol{r}$ is a point on the evaluation surface.

Note 2 to entry: Other local maxima (i.e. secondary peak spatial-average power density values) can exist (see 3.1.4).

3.1.4
secondary peak spatial-average power density
other local maxima of the spatial-average power density (*sPD*) values that are smaller than the peak spatial-average power density (*psPD*)

3.1.5
Poynting vector
$\boldsymbol{S}$
vector product of the electric field strength $\boldsymbol{E}$ and the magnetic field strength $\boldsymbol{H}$ of the electromagnetic field at a given point

Note 1 to entry: The flux of the Poynting vector through a closed surface is equal to the electromagnetic power passing through this surface.

Note 2 to entry: For a periodic electromagnetic field, the time average of the Poynting vector is a vector the direction of which, with certain reservations, can be considered as being the direction of propagation of electromagnetic energy and the magnitude of which can be considered as being the average power flux density.

Note 3 to entry: For a sinusoidal wave of angular frequency ω, the complex Poynting vector is expressed by Formula (2)

$$\boldsymbol{S} = \frac{1}{2} \boldsymbol{E} \times \boldsymbol{H}^* \tag{2}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are phasors and the asterisk denotes the complex conjugate.

Note 4 to entry: The Poynting vector has units of watt per square metre (W/m^2).

[SOURCE: IEC 60050-121:2019, 121-11-66 and IEC 60050-705:1995, 705-02-10, modified – The entries have been combined and rearranged; Note 4 has been added.]

3.1.6
plane wave equivalent approximation
estimation of the power density (PD) under the assumption that the evaluation surface is in the far-field

Note 1 to entry: In accordance with the plane wave equivalent approximation, PD = 377 × H^2 = E^2/377.

Note 2 to entry: This document provides criteria for the validity of the plane wave equivalent approximation using the applied reconstruction algorithm; see 7.4.2.1 and Annex H.

Note 3 to entry: Some documents and national regulations consider the associated term "plane-wave equivalent power density", which for uniform conformity evaluation purposes is applied regardless of whether the evaluation surface is in the far-field. In that case both 377 × H^2 and E^2/377 must be less than or equal to the applicable power density limit value.

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3.1.7
specific absorption rate
SAR
measure of the rate at which energy is absorbed per unit mass in a human body when exposed to a radio frequency electromagnetic field

Note 1 to entry: The SAR in the tissue-equivalent medium can be determined by the rate of temperature increase or by E-field measurements, according to Formula (3) and Formula (4)

$$SAR = \frac{\sigma E^2}{\rho} \tag{3}$$

$$SAR = c_{\mathrm{h}} \left.\frac{\partial T}{\partial t}\right|_{t=0} \tag{4}$$

where

SAR is the specific absorption rate in watts per kilogram;

E is the RMS value of the electric field strength in the tissue-equivalent medium in volts per metre;

σ is the electrical conductivity of the tissue-equivalent medium in siemens per metre;

ρ is the mass density of the tissue-equivalent medium in kilograms per cubic metre;

c_{h} is the specific heat capacity of the tissue-equivalent medium in joules per kilogram per kelvin;

$\left.\frac{\partial T}{\partial t}\right|_{t=0}$ is the initial time derivative of temperature in the tissue-equivalent medium in kelvin per second.

Note 2 to entry: A more general definition is that SAR is the time derivative of the incremental energy ($\mathrm{d}W$) absorbed by (dissipated in) an incremental mass ($\mathrm{d}m$) contained in a volume element ($\mathrm{d}V$) of given mass density (ρ), according to Formula (5)

$$SAR = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho\,\mathrm{d}V}\right) \tag{5}$$

Note 3 to entry: SAR is expressed in units of watt per kilogram (W/kg).

3.1.8
exposure ratio
ratio of exposure metric to the relevant exposure limit at a given operating frequency and location

Note 1 to entry: The exposure ratio can be expressed in percent.

3.1.9
total exposure ratio
sum of all applicable exposure ratios for simultaneous signal transmission at a given location

3.1.10
conservative exposure
conservative estimate
<of exposure> estimate of the exposure, including uncertainties as specified in this document, representative of and slightly higher than that expected to occur in the head or body of a significant majority of the human population during intended use of a wireless transmitting device

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3.2 Spatial, physical, and geometrical parameters associated with exposure metrics

3.2.1
averaging area
A_{av}
nominal size of the area used for calculating sPD (3.1.2)

Note 1 to entry: On a planar evaluation surface, sPD is calculated as the ratio of power density (3.1.1) integrated over the averaging area A_{av}. On a non-planar evaluation surface, the averaging area indicates the dimensions of the projection of the integration area of the power density on a planar surface.

Note 2 to entry: See details on averaging in 8.4 of IEC/IEEE 63195-2:2021.

3.2.2
measurement region
surface or volume over which the field measurements are performed

Note 1 to entry: If the measurement region and the evaluation surface (see 3.2.3) are different, the data at the evaluation surface will then be derived from data taken at the measurement region by means of reconstruction algorithms.

Note 2 to entry: The dimension, shape and orientation of the measurement region is determined by the test equipment manufacturer based on the measurement methodology and test setup conditions required for evaluating the DUT.

3.2.3
evaluation surface
virtual surface for the evaluation of the spatial-average power density (sPD) emitted by a DUT

Note 1 to entry: Typical evaluation surfaces that can be applied in this document are the inner shell of the SAM phantom with an added pinna, or a planar surface with finite or infinite extension.

Note 2 to entry: The evaluation of the $psPD$ (3.1.3) on the evaluation surface should yield a conservative estimate (3.1.10) of the exposure.

Note 3 to entry: In practice, an evaluation surface can be different from a measurement surface or area.

3.2.4
evaluation distance
distance between the DUT and the evaluation surface

Note 1 to entry: For body-worn device evaluations using a virtual flat phantom, the evaluation distance is from the DUT to the inner surface of the virtual phantom (i.e. the separation distance (3.2.5) plus the 2 mm shell thickness of a virtual phantom).

3.2.5
separation distance
distance between the DUT and the outer surface of a virtual phantom

3.2.6
pinna
auricle
cartilaginous projecting portion of the outer ear, consisting of the helix, lobule, and anti-helix

Note 1 to entry: The SAM phantom includes a representative pinna feature.

3.2.7
field impedance
wave impedance
ratio of the magnitude of the electric field (E-field) vector to the magnitude of the magnetic field (H-field) vector at a point in space

Note 1 to entry: In the far-field in air, the field impedance is equal to the characteristic impedance of free space, η_0. In the reactive near-field, the field impedance can be significantly different from the characteristic impedance of free space and it can vary strongly with location.

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3.2.8
near-field
region encompassed by the reactive near-field and the radiative near-field

Note 1 to entry: See also 3.2.10 and 3.2.9 for definitions of reactive near-field and radiative near-field, respectively.

3.2.9
radiative near-field
region of space between the reactive near-field and the far-field, wherein the predominant components of the electromagnetic field are those that represent a propagation of energy, and wherein the angular field distribution is dependent upon the distance from the antenna

Note 1 to entry: In the radiative near-field, the out-of-phase (i.e. evanescent) component of the electromagnetic field decays, and the in-phase (i.e. propagating) component of the electromagnetic field emerges.

[SOURCE: IEC 60050-712:1992, 712-02-04, modified – In the term, "radiating" has been replaced by "radiative". In the definition, "region" has been deleted after "near-field" and "far-field". The note has been replaced by a new note to entry.]

3.2.10
reactive near-field
region of space immediately surrounding an antenna, where the predominant components of the electric field and magnetic field are those that represent an exchange of reactive energy between the antenna and the surrounding medium, and where the electric field and magnetic field components are 90° out of phase

[SOURCE: IEC 60050-712:1992, 712-02-01, modified – In the definition, the electric field and magnetic field component phase difference has been added.]

3.2.11
far-field
region of the electromagnetic field of an antenna wherein the predominant components of the field are those that represent a propagation of energy, the angular field distribution is essentially independent of the distance from the antenna geometrical centre, and the ratio of predominant electric field and magnetic field components is constant and is equal to the wave impedance of 377 Ω

Note 1 to entry: For the purposes of this document, the boundary of the near-field and far-field is as specified in 7.4.2.1.

[SOURCE: IEC 60050-712:1992, 712-02-02, modified – In the definition, the distance to antenna geometrical centre has been clarified, and a phrase on the ratio of the electric field and magnetic field components has been added. The notes have been replaced by a new note to entry.]

3.3 Measurement instrumentation, field probe, and data-processing parameters

3.3.1
power density measurement
assessment of power density (PD) (3.1.1) by the use of a measurement apparatus and possibly the use of reconstruction

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3.3.2
reconstruction
use of algorithms to transform the measured fields to the power density at the evaluation surface

Note 1 to entry: Reconstruction algorithms include one or more of the following techniques:

- methodologies to retrieve field components and power densities (i.e. determined using field reconstruction) from the measured data (e.g. to retrieve the phase from the amplitude, or the H-field from the E-field (or vice versa).
- forward transformation and backward transformation to evaluate the field on other surfaces than the surfaces of measurements.

3.3.3
backward transformation
transformation of measured fields toward the source (i.e. against the direction of propagation)

3.3.4
forward transformation
transformation of measured fields away from the source (i.e. in the direction of propagation)

3.3.5
field probe
probe
device capable of measuring the electric field, the magnetic field, or both

Note 1 to entry: A field probe consists of one or more probe sensors and a conductive or non-conductive transmission line (e.g. fibre optic) that sends the measured signal to the readout electronics.

Note 2 to entry: A field probe can include a physical housing and electronics components.

3.3.6
probe sensor
element (e.g. small dipole or small loop antenna) that receives an electric field, a magnetic field, or power density at a point in space

Note 1 to entry: One or more probe sensors are contained in a field probe.

3.3.7
scanning system
mechanical, electro-mechanical, or electronic system, or a combination of those, capable of placing the field probe or multiple field-probe at specified positions with known accuracy

3.3.8
multiple field-probe
<system> device comprised of a number of field probes, arranged, oriented and excited to obtain a prescribed electric field, magnetic field or both simultaneously

Note 1 to entry: The multiple field-probes in a system are usually identical and congruent by translation or by rotation about an axis; moreover, in general they are regularly spaced with conductive or non-conductive transmission lines that send the measured signal(s) to the readout electronics.

3.3.9
phasor
complex number expressing the magnitude and phase of a time-varying quantity

Note 1 to entry: Unless otherwise specified, phasor notation is used only within the context of steady state alternating linear systems.

Note 2 to entry: In polar coordinates, a phasor can be written as $Ae^{j\theta}$, where A is the amplitude or magnitude, and θ is the phase angle.

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3.3.10
phasor probe
probe along with readout electronics that enables the measurement of the phasor of a magnetic field vector or an electric field vector

3.3.11
axial isotropy
maximum deviation of the PD measured when rotating through 360° the source or the probe tip around its major axis, with the propagation vector (k-vector) of the incident plane wave parallel to the probe axis

3.3.12
hemispherical isotropy
probe isotropy
ratio of the highest to lowest indication from the probe exposed to a constant field strength when the probe orientation is varied through the range of relevant angles that cover the incidence angles that are potentially spanned during DUT testing

Note 1 to entry: For some probe technologies, multiple measurements with different probe orientations followed by an evaluation are required in order to determine the field vector orientation (e.g. see Pfeifer et al. [4]); hemispherical isotropy can be derived from those results.

3.3.13
cross coupling
signal reading at one sensor port that is due to measurement at another sensor within a field probe

Note 1 to entry: Cross coupling is a result of imperfect isolation of the signals. Cross coupling can occur along the transmission lines from the sensor or in the data acquisition electronics.

3.3.14
linearity error
maximum deviation of a measured quantity from the expected values specified by a reference line over the measurement range

3.3.15
measurement drift
continuous or incremental change in measured quantity over time, due to changes in metrological properties of a measuring instrument

Note 1 to entry: This is separate from DUT drift addressed in 7.4.4.

3.3.16
readout electronics
measurement system component that connects to the electric field or magnetic field probe and provides a conversion of the measured values to the post processor of the measurement system

3.3.17
response time
time required by the measuring equipment to reach 90 % of its final value after a step variation of the input signal

3.3.18
sensitivity of a measurement system
ratio of the magnitude of the system response (e.g. voltage) to the magnitude of the quantity being measured (e.g. electric field strength squared)

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3.3.19
signal-to-noise ratio
relative magnitude of the desired signal with respect to the total of all undesired signals in a measurement

Note 1 to entry: The signal-to-noise-ratio is often expressed in decibel (dB).

3.3.20
device holder
fixture constructed of low-loss dielectric material that is used to hold the DUT in the required test position during PD measurement

3.3.21
scattering
deflection of electromagnetic fields, causing a change in the local field distribution and the direction of propagation

Note 1 to entry: Scattering can be caused by the measurement equipment or surrounding environment.

3.3.22
validation
verification (3.3.24) where the specified requirements are adequate for an intended use

[SOURCE: ISO/IEC 17025:2017, 3.9 [5]]

3.3.23
system validation
validation (3.3.22) that the accuracy of the measurement system is adequate for use in accordance with the requirements of this document, including validating that the measurement system operates within the stated measurement uncertainty

Note 1 to entry: Although users of systems can perform system validations, generally it is a complex, specialized, and extensive process, and therefore in some cases is performed by the system manufacturer.

3.3.24
verification
provision of objective evidence that a given item fulfils specified requirements

[SOURCE: ISO/IEC 17025:2017, 3.8 [5]]

3.3.25
relative system check
verification (3.3.24) of the repeatability of the measurement system using a source with a reference value before performing conformity testing

3.3.26
absolute system check
verification (3.3.24) of the absolute accuracy of a measurement system using a source with a traceable absolute target value

Note 1 to entry: Absolute system checks are performed at the user's site.

Note 2 to entry: One purpose of the absolute system check is to verify that the shipment and installation at the user site did not affect the performance of the measurement system.

3.4 RF power parameters

3.4.1
output power
power at the output of the RF transmitter when the antenna, or a load with the same input impedance as the antenna, is connected to it

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3.4.2
conducted power
power delivered by the power amplifier of the device to 50 Ω matched load

3.4.3
accepted power
net power
power delivered to an antenna

Note 1 to entry: The accepted power, P_{acc}, is lower than the forward power, P_f (measured into a 50 Ω load), due to antenna mismatch according to $P_{acc}/P_f = \left(1-|S_{11}|^2\right)$, where S_{11} is the reflection coefficient of the antenna.

3.4.4
equivalent isotropically radiated power
EIRP
product of the power supplied by a radio transmitter to an antenna and the absolute gain of the antenna in a given direction

Note 1 to entry: Although not indicated in IEV or ITU definitions, some literature synonymously uses the term effective isotropic radiated power.

[SOURCE: IEC 60050-712:2021, 712-02-51]

3.4.5
total radiated power
TRP
integral of the equivalent isotropically radiated power (EIRP) of an antenna in all directions in the far-field

Note 1 to entry: TRP is given by Formula (6), where ϕ and θ are angles of azimuth and elevation, respectively, in a spherical coordinate system.

$$TRP = \frac{1}{4\pi}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} EIRP(\theta,\phi)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi \tag{6}$$

Note 2 to entry: If the antenna were enclosed in a perfectly absorbing sphere, the TRP would be the power that would be absorbed by that sphere.

Note 3 to entry: TRP is related to the accepted power, P_{acc}, and the radiation efficiency, η_{eff}, by the formula $TRP = \eta_{eff} \times P_{acc}$.

3.5 Test device technical operating and antenna parameters

3.5.1
operating mode
wireless protocol or standard used by a device to communicate with another terminal or host network

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3.5.2
channel
RF channel
frequency channel
part of the frequency spectrum intended to be used for the transmission of signals and which may be defined by two specified limits, or by its centre frequency and the associated bandwidth, or by any equivalent indication

Note 1 to entry: The number of RF channels and the corresponding channel bandwidth can vary among individual wireless technologies, and are subject to national frequency allocations. For the purpose of this document, PD measurements are performed at specific channels; for example, the high, middle, and low channels of the transmission band.

[SOURCE: IEC 60050-701:1988, 701-02-05]

3.5.3
frequency band
transmitting frequency range associated with a specific wireless communication operating mode

Note 1 to entry: Transmitting frequency range depends on (national) spectrum allocations.

Note 2 to entry: Operating mode is also known as "radio access technology (RAT)."

3.5.4
antenna sub-array
subset of radiating elements in an array that operate collectively

Note 1 to entry: Antenna elements can be used separately by two or more sub-arrays.

3.5.5
array
array antenna
antenna array
antenna comprised of a number of generally identical radiating elements, arranged, oriented and excited to obtain a prescribed radiation pattern

Note 1 to entry: The IEV also includes phased array antenna (IEV 712-03-20): an array antenna whose beam direction or radiation pattern is controlled primarily by the relative phase of excitation of the different radiating elements of the array.

[SOURCE: IEC 60050-712:1992, 712-01-05]

3.5.6
codebook
description of all applicable element-feed amplitude and phase combinations supported by antenna array or antenna sub-array in a DUT

Note 1 to entry: IEC/IEEE 63195-2:2021 defines codebook as set of all possible excitation vectors. The excitation vectors correspond to all applicable element-feed amplitude and phase combinations.

3.5.7
correlated signals
signals yielding non-zero time-domain correlation integral at some time instant

Note 1 to entry: Details on this definition are described in IEC TR 62630:2010 [6].

3.5.8
proximity sensor
internal sensor or combination of sensors of the DUT utilized for the detection of the user proximity for the purpose of limiting transmitter power to facilitate conformity with RF exposure limits

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3.5.9
radiation efficiency
ratio of the total radiated power (TRP) (3.4.5) of an antenna to the accepted power (3.4.3) to the antenna

Note 1 to entry: TRP is related to the accepted power, P_{acc}, and the radiation efficiency, η_{eff}, by the formula $TRP = \eta_{eff} \times P_{acc}$.

3.5.10
time averaging
temporal integration of the measured signal normalized to the integration period

3.6 Test device physical configurations

3.6.1
device under test
DUT
test device
device that is tested according to the procedures described in this document to determine the PD level

Note 1 to entry: A DUT may be further categorized as a body-worn, body-supported, desktop, front-of-face, hand-held, limb-worn, clothing-integrated, or generic device.

3.6.2
multi-band
<wireless communication device> capable of operating in more than one frequency band

3.6.3
generic device
device that does not belong to any of the specific device categories

Note 1 to entry: Specific device categories are defined in 3.6.5, 3.6.6, 3.6.7, 3.6.8, 3.6.9, 3.6.10, and 3.6.11.

3.6.4
intended use
use for which a device is intended, for the full range of available functions, according to the specifications, instructions and information provided by the DUT manufacturer in the user documentation

Note 1 to entry: According to CENELEC [7], [8], conformity evaluations for Europe take into account all intended operating conditions and the reasonably foreseeable conditions of use.

3.6.5
body-worn device
device containing one or more wireless transmitters or transceivers that is positioned in close proximity to a person's torso or limbs (excluding the head) by means of a carrying accessory during its intended use or operation of its radio functions

3.6.6
body-supported device
device containing one or more wireless transmitters or transceivers whose intended use includes transmitting with any portion of the device being placed against a user's body

3.6.7
desktop device
device placed or mounted on a desk, table, or similar supporting structure, with antennas intended to be operated at or closer than 200 mm from the human body

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3.6.8
front-of-face device
hand-held device containing one or more wireless transmitters or transceivers operated in close proximity (within 200 mm) to the face

3.6.9
hand-held device
portable device which is operated in a user's hand at a distance of over 200 mm from the head or torso during its intended use

3.6.10
laptop device
device, containing one or more wireless transmitters or transceivers, that can sit on the user's lap and is not intended for hand-held use

Note 1 to entry: Laptop device types include laptop (notebook) computers, typically comprised of separate keyboard and display sections connected through a hinge, and tablet computers that typically have a single-section construction where the display section also serves as input interface using a stylus or virtual keyboard.

3.6.11
limb-mounted device
device containing one or more wireless transmitters or transceivers whose intended use includes being strapped onto the arm or leg of the user while transmitting

Note 1 to entry: Limb-mounted device types include wrist-mounted, ankle-mounted, and forearm-mounted devices.

3.6.12
accessory
device supplementing a main device or apparatus, but not forming part of it, that is needed for its operation or to confer on it specific characteristics

EXAMPLE 1 Accessories for holding, affixing, or otherwise carrying, wearing, or attaching the device, as well as providing spacing from the body (e.g. a belt-clip, wrist-strap or any other body strap, or lanyard for wearing the device using a necklace).

EXAMPLE 2 Electronic accessories for performing specialized tasks or which provide additional features (e.g. Global Positioning System (GPS) modules, outboard printers, MPEG-1 Audio Layer 3 (MP3) players, cameras or viewing devices).

EXAMPLE 3 Electronic accessories providing audio or video input or output (e.g. headsets, microphones, cameras).

EXAMPLE 4 Accessories providing enhanced RF capability to the device (e.g. original, replacement, or auxiliary antennas).

EXAMPLE 5 Batteries and related direct current (DC) power components.

EXAMPLE 6 Combinations of accessories, where two or more of the items of the preceding examples are combined within one component (e.g. belt clip with built-in short-range wireless communications technology and "pigtail" audio cable to device).

[SOURCE: IEC 60050-151:2001, 151-11-24]

3.7 Uncertainty parameters

3.7.1
uncertainty
confidence range of the assessed value

3.7.2
standard uncertainty
estimated standard deviation of a measurement or simulation result, equal to the positive square root of the estimated variance

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3.7.3
combined uncertainty
estimated standard deviation of the measurement or simulation result obtained by combining the individual standard uncertainties of both Type A and Type B evaluations using the "root-sum-square" method of combining standard deviations that are obtained by taking the positive square root of the estimated variances

3.7.4
expanded uncertainty
quantity defining an interval about the result of a measurement or simulation that is expected to encompass a distribution of values within a specified confidence interval that can reasonably be attributed to the measurand

3.7.5
uncertainty evaluation
evaluation of uncertainty by the statistical analysis of series of observations (Type A) or by other means (Type B)

4 Symbols and abbreviated terms

4.1 Symbols

4.1.1 Physical quantities

The internationally accepted SI units are used throughout the document.

Symbol	Quantity	Unit	Dimensions
α	attenuation coefficient	reciprocal metre	1/m
P	power	watt	W
J	current density	ampere per square metre	A/m^2
σ	electric conductivity	siemens per metre	S/m
E	electric field strength	volt per metre	V/m
f	frequency	hertz	Hz
PD	power density	watt per square metre	W/m^2
S	Poynting vector	watt per square metre	W/m^2
H	magnetic field strength	ampere per metre	A/m
ρ	mass density	kilogram per cubic metre	kg/m^3
δ	penetration depth	metre	m
μ	permeability	henry per metre	H/m
sPD	spatial-average power density	watt per square metre	W/m^2
$sPD_{\mathrm{n+}}$	surface-normal propagation-direction spatial-average power density	watt per square metre	W/m^2
$sPD_{\mathrm{tot+}}$	total propagating spatial-average power density	watt per square metre	W/m^2
$sPD_{\mathrm{mod+}}$	total spatial-average power density considering reactive near-field effects	watt per square metre	W/m^2
$psPD$	peak spatial-average power density	watt per square metre	W/m^2
$psPD_{\mathrm{n+}}$	surface-normal propagation-direction peak spatial-average power density	watt per square metre	W/m^2
$psPD_{\mathrm{tot+}}$	total propagating peak spatial-average power density	watt per square metre	W/m^2

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Symbol	Quantity	Unit	Dimensions
$psPD_{\text{mod+}}$	total peak spatial-average power density considering reactive near-field effects	watt per square metre	W/m^2
c_h	specific heat capacity	joule per kilogram per kelvin	J/(kg K)
ε	permittivity	farad per metre	F/m
SAR	specific absorption rate	watt per kilogram	W/kg
T	temperature	kelvin	K
λ	wavelength	metre	m

NOTE In this document, temperature is quantified in degrees Celsius, as defined by: T (°C) = T (K) − 273,15.

4.1.2 Constants

Symbol	Physical constant	Magnitude
c	speed of light in vacuum	$2{,}998 \times 10^8$ m/s
η_0	characteristic impedance of free space	376,73 Ω
ε_0	permittivity of free space	$8{,}854 \times 10^{-12}$ F/m
μ_0	permeability of free space	$4\pi \times 10^{-8}$ H/m

4.2 Abbreviated terms

2D two-dimensional
3D three-dimensional
B-M back-to-mouth
CAD computer aided design
CP cyclic prefix
CW continuous wave
DFT-s discrete Fourier transform spread
DUT device under test
E-field electric field
EIRP equivalent isotropically radiated power
EMC electromagnetic compatibility
ER exposure ratio
ERP ear reference point
FDTD finite-difference time-domain
GTEM gigahertz transverse electromagnetic
H-field magnetic field
ICNIRP International Commission on Non-Ionizing Radiation Protection
MIMO multiple input multiple output
N-F neck-to-front
NR new radio
OFDM orthogonal frequency-division multiplexing
PAPR peak to average power ratio
PD power density
QAM quadrature amplitude modulation
QPSK quadrature phase shift keying

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RB	resource block
RF	radio frequency
RMS	root mean square
RSS	root sum square
SAM	specific anthropomorphic mannequin
SAR	specific absorption rate
TER	total exposure ratio
TRP	total radiated power
VNA	vector network analyser

5 Quick start guide and application of this document

5.1 Quick start guide

The quick start guide shown in Figure 1 and the evaluation plan check-list shown in Table 1 provide a high-level overview of the PD measurement procedure. For the details of each step, refer to the relevant clause specified in Figure 1 and Table 1.

NOTE In the far-field of a source at separation distances less than 200 mm, a simpler measurement system and test procedures can be used, such as described in IEC 62311:2019 [9][2].

2 Numbers in square brackets refer to the Bibliography.

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Table 1 – Evaluation plan check-list

Stage	Evaluation steps	Action
Evaluation plan check-list Planning of the measurement configurations	– What type of device is being evaluated? – Review of antennas, possible beam-steering options and supported wireless technologies, single antenna or require combinations of exposure from multiple antennas. – What are the applicable evaluation surfaces? – Working under laboratory conditions and following good laboratory practice and documentation, prepare to conduct the necessary evaluation.	Complete evaluation plan check-list.
Preliminary actions and Relative system check	– An environmental measurement shall be performed, and the data recorded (6.2). – Relative system check shall be performed to verify that the system components are working correctly (Clause A.3).	Shall be performed before starting a project and repeated in accordance with 7.2.1.
DUT setup Preparation of DUT	The protocol for *psPD* assessment identifies the applicable configurations that shall be tested. The essential steps include: – preparing the DUT by establishing a connection to a network simulator; – configuring the DUT to operate on the appropriate test frequencies, wireless modes, and exposure conditions; – configuring the DUT to operate on the appropriate beam-steering options; – positioning the DUT in relation to the measurement region.	Ensure the DUT is configured in the correct way and radiating appropriately for the test case, and positioned correctly in relation to the measurement region.
PD measurement procedures General *psPD* procedure	– This stage is the actual procedure for the measurement of *psPD*. – The procedure is iterative to ensure that the highest value of the *psPD* of a DUT is captured. – This is done by a systematic process looking at all device positions, configurations, and operating modes in all frequency bands accordingly (7.2.3).	Determining highest *psPD*. Ensure the rationale for test reduction is recorded and reported if used.
Uncertainty evaluation	– Requirements and approximation formulas are provided (Clause 8), enabling the estimation of each individual uncertainty component. – The uncertainty budget shall cover the appropriate frequency range with regards to equipment used in the *psPD* system.	Determine uncertainty and complete the uncertainty table.
Reporting *psPD* results	– The final report describes the results of the evaluations, provides sufficient technical details to allow for repeatability of the evaluations performed, and reports the results by comparison with the relevant limit (Clause 9). – The measurement report shall contain sufficient details and information for demonstrating conformity to the requirements of this document.	Prepare the final measurement report along with addressing the requirements listed in Clause 9.

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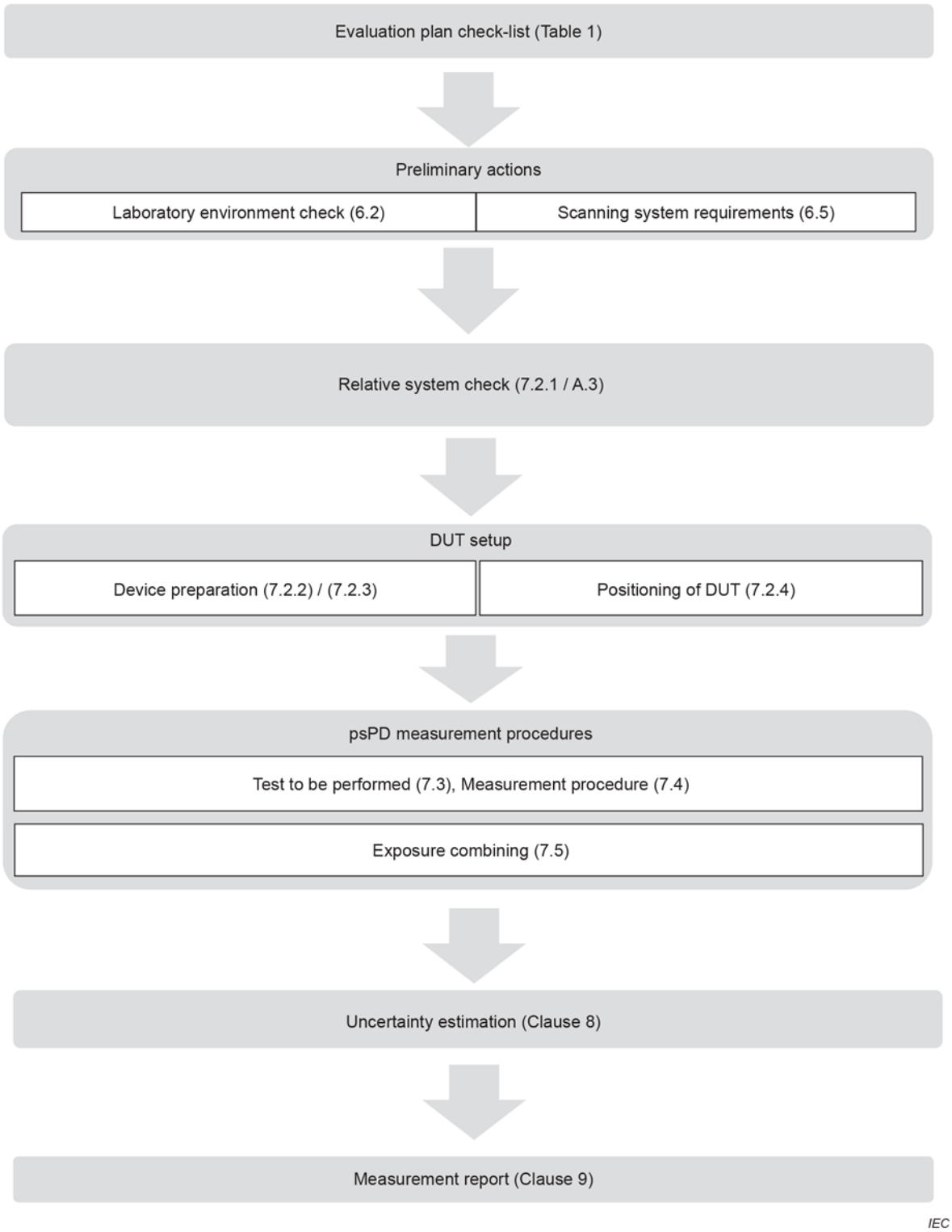

Figure 1 – Quick Start Guide

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5.2 Application of this document

This document and IEC/IEEE 63195-2:2021 were developed in parallel in two joint working groups of IEC and IEEE to prepare procedures for conformity evaluation to exposure limits on the incident power density under particular consideration of the exposure from wireless devices of the new fifth generation (5G) mobile technology operating in a frequency range from 6 GHz to 300 GHz. This document specifies measurement procedures, and IEC/IEEE 63195-2:2021 specifies computational procedures.

After the fundamental work on the measurement procedures for conformity evaluation at frequencies above 10 GHz had been documented in IEC TR 63170:2018 [10], both this document and IEC/IEEE 63195-2:2021 were developed in a comparatively short time period of two years. In parallel, the ICNIRP [2] and TC95 of the IEEE ICES revised their exposure guidelines and included new basic restrictions and reference levels for the frequency range of 6 GHz and above. These are based on the absorbed/epithelial power density or incident power density, respectively, averaged over a square area of 1 cm^2 or 4 cm^2.

This document contains all relevant specifications for the application of measurement procedures for conformity evaluation. While parts of it can be applied independently from the computational standard IEC/IEEE 63195-2:2021, it refers to the post processing methods for power density averaging and maximization of the incident power density that are common to both this document and IEC/IEEE 63195-2, but are specified only in IEC/IEEE 63195-2:2021. Likewise, computational conformity evaluation is described in IEC/IEEE 63195-2:2021. For validations of numerical modelling results by measurements, the methods of this document are required.

5.3 Stipulations

Due to the constraints on the time available for the development of this document and IEC/IEEE 63195-2:2021, practical options needed to be found regarding the interpretation of the new exposure guidelines for the assessment of the conformity with the new limits. These concern the construction of the averaging area and the calculation of the spatial average power density on this averaging area. Regarding the calculation of the spatial average power density, different methods are specified with the objectives to warrant compatibility with exposure evaluations obtained according to IEC TR 63170:2018 [10] and to consider exposure conditions other than perpendicular incidence in the far-field. Annex I discusses the options and their rationales.

These options do not impair the applicability of the methods specified in IEC/IEEE 63195-2 and this document for the conformity evaluation with the reference levels specified in the exposure guidelines.

6 Measurement system and laboratory requirements

6.1 General requirements

A PD measurement system is used to determine the peak spatial-average power density ($psPD$) on the evaluation surface in accordance with the methods described in Clause 7. The measurement protocol in this document is based on mechanically positioning field probes in a grid relative to the DUT to scan the electric field or magnetic field distributions, or both. The following are minimum requirements of the measurement system.

a) Measurements shall be performed in a controlled laboratory (see 6.2).

b) The measurement system shall consist of the field probe(s) (see 6.3), measurement instrumentation (see 6.4), a scanning system (see 6.5), a DUT holder (see 6.6) and post-processing software (see 6.7). The post-processing software may include field reconstruction algorithms.

c) The measurement system shall be capable of determining the sPD on the required evaluation surface.

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d) Uncertainties of the measured field components and power density results (i.e. determined using field reconstruction) shall be assessed and provided (see Clause 8).

e) The measurement system shall determine the sPD on the evaluation surface using the measured field components and power densities (i.e. determined using field reconstruction), of which the $psPD$ shall be calculated. The uncertainty of the $psPD$ calculation shall be provided based on the uncertainty of the measured field components and power densities (i.e. determined using field reconstruction) (see Clause 8).

f) The dynamic range of the sPD for which the uncertainty budget is valid shall be from at most 20 % to at least 200 % (less than −7 dB to more than +3 dB) of the applicable exposure limit.

g) The noise floor of the measurement system shall be at least 10 dB below the lower end of the dynamic range of the PD, so that the influence of noise on the measurement uncertainty is small.

h) The maximum expanded uncertainty (k = 2) of the $psPD$ assessment shall not be larger than ±2 dB (−37 % to +58 %) over the dynamic range.

i) The bandwidth of the measurement system shall be valid for the wireless communication signals and systems tested.

j) The measurement system shall have valid calibration across the frequency range tested.

k) The manufacturer of the measurement system shall report to the user the limitations of the system relative to this document. This includes the frequency range, the bandwidth, the locations of the evaluation surface relative to the DUT, the dynamic range, and the measurement uncertainty.

l) The components of the measurement system that directly affect the measurement accuracy (e.g. field probes, measurement instrumentation) shall have calibration traceable to international standards.

m) The measurement system shall be validated as a complete and calibrated system (see Clause A.5). System validation is required whenever modifications have been made to the system (e.g. software version, or different type or version of measurement components).

n) Where this document explicitly specifies performance characteristics for the measurement system or a part of the measurement system, the manufacturer of the system or its parts, or the system integrator, shall document conformity with the provisions of this document.

Conformity with the preceding general requirements shall be documented by the system manufacturer or system integrator.

NOTE 1 Simplified measurement systems and test procedures can be applied if the body is always in the far-field of the source (e.g. see IEC 62311:2019 [9]), which can also include separation distances closer than 200 mm.

NOTE 2 The ICNIRP RF EMF Guidelines [2] state that reference levels (incident power density) cannot be used to determine conformity within reactive near-field, basic restrictions (absorbed power density) should be used instead. Based on the ICNIRP definition of reactive near-field, this limitation is applicable to procedures of this document at frequencies below 24 GHz. IEC TC 106 and IEEE ICES are considering to develop an international standard for absorbed or epithelial power density in future.

NOTE 3 System validation methods are currently specified in this document for the frequency range 6 GHz to 100 GHz, which covers all devices currently available. Extension to 300 GHz of the validation procedures will be specified in a future revision.

NOTE 4 To quantify the measurement reproducibility of a system, interlaboratory comparisons (Annex F) using sources that are representative of the radiating characteristics of tested devices can be conducted.

6.2 Laboratory requirements

The tests shall be performed in a laboratory conforming to the following requirements.

a) The ambient noise for any measurement shall correspond to less than −20 dB (1 %) of either the applicable power density limit or the peak measured field, whichever is higher.

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b) The influence of reflections from objects in the laboratory (including the scanning measurement system, cables, walls, and the DUT holder) on the measurements shall be less than −17 dB (2 %) of the applicable power density limit. See 8.5.9 to determine the influence of reflections. This shall be evaluated at least annually.

c) The ambient temperature shall be in the range for which the calibration of the system component is valid and the transmission variation of the DUT by temperature due to ambient temperature is less than 5 % (e.g. between 18 °C and 25 °C) (see 8.5.8). It shall also vary by less than ±2 °C with respect to the ambient temperature during the measurement.

d) The measurement equipment shall have been powered on and allowed to warm up in the laboratory in accordance with manufacturer's stabilization time.

Conformity with these laboratory requirements shall be documented in the measurement report.

6.3 Field probe requirements

The measurement system includes one or more field probes; multiple field-probe systems can significantly reduce the measurement time. Each field probe shall conform to the following requirements.

a) The field probe(s) shall measure the electric field or the magnetic field or both.

b) The cross-coupling level between field components shall be such that the maximum expanded uncertainty requirements in 6.1 are met.

c) The field probe shall measure the phase of the field unless the evaluation surface is in the far-field (see Table 2 of 7.4.2.1) or unless field reconstruction techniques are applied to estimate the power density correctly.

d) The field probe dynamic range shall be such that the system dynamic range requirements in 6.1 are met.

e) The field probe size and construction shall ensure that the effect of scattering from the probe on the fields transmitted by the DUT is within the expanded uncertainty for probe scattering as described in 8.4.7.

f) The field probe shall be calibrated according to the requirements in Annex C. The probe may be calibrated separately from the rest of the measurement system if the same electrical interface characteristics are used during calibration as during measurements. It is preferable not to calibrate the probe separately from the rest of the measurement system. If the probe is calibrated separately, the calibration uncertainty should include statistical interdependence with a signal reading instrument.

g) The field probe calibration report shall document at least the uncertainties and the associated validity restrictions of mechanical offset (8.4.10), frequency response (8.4.3), sensitivity, linearity error (8.4.6), isotropy (8.4.5), cross coupling (8.4.4), and field impedance dependence (8.4.12). Any dependence of these quantities on frequency and bandwidth shall also be reported.

Conformity with these field probe requirements shall be documented by the manufacturer of the measurement system.

6.4 Measurement instrumentation requirements

The field probe output is processed by the measurement instrumentation, which conforms to the following requirements.

a) The measurement instrumentation shall receive the signal measured by the field probe and provide it to a computer for evaluation.

NOTE The computer can be integrated with the measurement instrumentation, separate from it, or both.

b) The measurement instrumentation shall be calibrated. It may be calibrated separately from the probe if the same input and electrical interface characteristics are used during calibration as during measurements.

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The measurement instrumentation may perform amplification, frequency filtering or other signal processing. It may also account for signal compression, amplifier non-linearities and other non-linear effects.

Conformity with these measurement instrumentation requirements shall be documented by the manufacturer of the measurement system.

6.5 Scanning system requirements

6.5.1 Single-probe systems

The scanning system positions the field probe on the measurement region. The requirements of the scanning system are as follows.

a) The scanning method shall be reported, including whether it performs two-dimensional (2D) or three-dimensional (3D) scans.

b) The algorithm for determining the measurement grid, if a fixed grid is not used, shall be reported.

c) The scanning system shall restrict the field probe locations during measurement to the region where the influence of the field impedance on the measurement is within the stated uncertainty (see 8.4.12). This uncertainty shall not be greater than 0,5 dB.

d) The scanning system shall be capable of positioning the field probe over a large enough measurement region such that the $psPD$ can be determined at any point on the evaluation surface so to meet the stated REC uncertainty (see 8.4.18).

e) The accuracy and repeatability of the field probe positioning shall be reported, and they shall be sufficient to ensure that the measurement uncertainty of the $psPD$ is within the stated PPO uncertainty (see 8.4.8). The tolerance of field probe positioning shall also be sufficient to combine exposures from multiple antennas or multiple transmitters (see 7.5).

f) The scanning system shall be capable of rotating the field probe, if necessary, to capture the required field components and power densities (i.e. determined using field reconstruction). The accuracy and repeatability of field probe orientation shall be reported.

g) The scanning resolution shall be sufficient to maintain the measurement uncertainty of the $psPD$ within the stated uncertainty.

h) At each field probe location, the scanning system shall be capable of keeping the field probe in place for a sufficiently long time with respect to the integration time, as determined according to 8.5.3.

NOTE Scanning over the measurement region can include a combination of fast scans and full scans to reduce the measurement time, as long as this does not increase the measurement uncertainty. See 7.4.1 for more information.

Conformity with these scanning system requirements shall be documented by the manufacturer of the measurement system.

6.5.2 Multiple field-probe systems

The scanning system with multiple field-probes is in general regularly spaced configuration that manages the relative positioning of the field probes with respect to the DUT, such that the measurement region is covered. The requirements of the scanning system are as follows.

a) The scanning method shall be documented, including whether it performs 2D or 3D scans.

b) The algorithm for determining the measurement grid, if it does not measure a fixed grid, shall be documented.

c) The uncertainty of the relative position of the field probes with respect to the DUT shall be within the uncertainty for probe positioning offset (PPO; see 8.4.8).

d) The scanning system shall be capable of covering a large enough measurement region such that the $psPD$ can be determined at any point on the evaluation surface.

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e) The accuracy and repeatability of the positioning shall be reported, and they shall be sufficient to ensure that the measurement uncertainty of the $psPD$ is within the stated uncertainty. The tolerance of field probe positioning shall also be sufficient to combine exposures from multiple antennas or multiple transmitters (see 7.5).

f) The scanning system shall be capable of rotating the field probes and/or the DUT, if necessary, to capture the required field components and power densities (i.e. determined using field reconstruction). The accuracy and repeatability of field probes and/or DUT orientation shall be reported.

g) Minimal separation distance that ensures sufficiently low uncertainty contribution from the probe mutual coupling, such that the maximum expanded uncertainty requirement in 6.1 is met, shall be specified by the system manufacturer.

h) The scanning resolution shall be sufficient to maintain the measurement uncertainty of the $psPD$ within the stated tolerance.

i) For each acquisition, the scanning system shall be capable of keeping the field probes or the DUT or both in place for a sufficiently long time with respect to the integration time, as determined according to 8.5.3.

NOTE 1 Scanning over the measurement region can include a combination of fast scans and full scans to reduce the measurement time, as long as this does not increase the measurement uncertainty. See 7.4.1 for more information.

NOTE 2 The scanning system can be employed with combination of a DUT positioning system to reduce the measurement uncertainties such as the phase and amplitude variations due to cable bending.

Conformity with these scanning system requirements shall be documented by the manufacturer of the measurement system.

6.6 Device holder requirements

The device holder maintains the DUT in position during the measurement. The requirements of the device holder are as follows.

a) The positions and orientations shall enable the measurement of the DUT in all required measurement regions.

b) The device holder shall enable known and repeatable positioning and orientation of the DUT.

c) The device holder, including its supporting structure, shall be designed to minimize the perturbation of the fields from the DUT. The parts of the device holder that are in direct contact with the DUT shall be made of materials having a loss tangent ≤ 0,05 and relative permittivity ≤ 1,2.

   This requirement can be suppressed when the device holder is in direct contact with the DUT sufficiently far away from the radiating antenna. Rationale for use of such materials shall be documented in test report.

d) The reflections due to the device holder structure shall be less than −20 dB at the location of the DUT.

e) The device holder uncertainty shall be determined according to 8.5.5.

Conformity with these device holder requirements shall be documented by the manufacturer of the measurement system.

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6.7 Post-processing quantities, procedures, and requirements

6.7.1 Formulas for calculation of sPD

6.7.1.1 General

The sPD is evaluated at the location $\boldsymbol{r}$ as a function of the complex Poynting vector $\boldsymbol{S}$. Depending on the dominant direction of incidence and polarization of the electromagnetic field, or with exposure in the near-field of a DUT, 6.7.1.2, 6.7.1.3, and 6.7.1.4 specify the formulas for calculation of sPD for the different specifications of PD. Annex I provides rationales for the distinct PD specifications. Weighting functions in the integrands of Formula (7), Formula (8), and Formula (11) serve to avoid contributions, by scaling down the integrand at these regions to zero, from regions where the power density is oriented outward from the evaluation surface, or due to numerical inaccuracies for surfaces that are almost parallel to the direction of the Poynting vector.

NOTE 1 The formula used to calculate the PD depends on the applicable exposure guidelines or national regulations.

NOTE 2 The direction of the power density relative to the orientation of the evaluation surface was not considered in IEC TR 63170:2018 [10]. For compatibility with results that were assessed according to [10], weighting functions of Formula (8) and Formula (11) are not applied.

6.7.1.2 Surface-normal propagation-direction power density into the evaluation surface – $sPD_{\mathrm{n+}}$

The surface-normal propagation-direction power density into the evaluation surface, $sPD_{\mathrm{n+}}$, shall be calculated according to Formula (7).

$$sPD(\boldsymbol{r}_0) = \frac{1}{\hat{A}(\boldsymbol{r}_0)} \int_{A(\boldsymbol{r}_0)} \Re\{\boldsymbol{S}(\boldsymbol{r})\} \cdot \boldsymbol{n}_A(\boldsymbol{r}) \cdot \Theta\left[\Re\{\boldsymbol{S}(\boldsymbol{r})\} \cdot \boldsymbol{n}_A(\boldsymbol{r})\right] \mathrm{d}\hat{A}(\boldsymbol{r}) \tag{7}$$

where

$\Re\{\boldsymbol{S}(\boldsymbol{r})\}$ is the real part of the complex Poynting vector $\boldsymbol{S}$ at the location $\boldsymbol{r}$;

$\boldsymbol{n}_A(\boldsymbol{r})$ is the normal vector of the evaluation surface at the location $\boldsymbol{r}$ pointing into the evaluation surface, with $\|\boldsymbol{n}_A(\boldsymbol{r})\| = 1$;

$\Theta(x)$ is the Heaviside (unit step) function of x;

$\hat{A}(\boldsymbol{r}_0)$ is the evaluation surface at to the location $\boldsymbol{r}$;

$\boldsymbol{r}_0$ is the location of the centre point.

NOTE 1 The surface normal propagating power density into the evaluation surface as defined in IEC TR 63170:2018 [10] corresponds to $sPD_{\mathrm{n+}}$ with $\Theta(x) = 1$.

NOTE 2 Formula (7) corresponds to power density crossing a surface A, i.e. the energy per unit time and unit area crossing a surface of area A_{av}.

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6.7.1.3 Total propagating power density into the evaluation surface – $sPD_{\text{tot+}}$

The total propagating power density into the evaluation surface, $sPD_{\text{tot+}}$, shall be calculated according to Formula (8), along with Formula (9) and Formula (10).

$$sPD(\boldsymbol{r}_0) = \frac{1}{\hat{A}(\boldsymbol{r}_0)} \int_{A(\boldsymbol{r}_0)} \left\| \Re\{\boldsymbol{S}(\boldsymbol{r})\} \right\| \cdot \Xi\left\{\cos^{-1}\left[\boldsymbol{n}_R(\boldsymbol{r}) \cdot \boldsymbol{n}_A(\boldsymbol{r})\right]\right\} \mathrm{d}\hat{A}(\boldsymbol{r}) \tag{8}$$

with

$$\boldsymbol{n}_R(\boldsymbol{r}) = \Re\{\boldsymbol{S}(\boldsymbol{r})\} / \left\| \Re\{\boldsymbol{S}(\boldsymbol{r})\} \right\| \tag{9}$$

$$\Xi(\theta) = \begin{cases} 1, & 0 \le \theta < 85° \\ 1 - (\theta - 85°)/5°, & 85° \le \theta < 90° \\ 0, & \theta \ge 90° \end{cases} \tag{10}$$

$\left\| \Re\{\boldsymbol{S}(\boldsymbol{r})\} \right\|$ is the magnitude of the real part of the complex Poynting vector $\boldsymbol{S}$ at the location $\boldsymbol{r}$

and the other terms are as specified in 6.7.1.2.

NOTE 1 The total propagating power density into the evaluation surface as defined in IEC TR 63170:2018 [10] corresponds to $sPD_{\text{tot+}}$ with $\Xi(\theta) = 1$.

NOTE 2 Formula (8) corresponds to magnitude of the real part of the Poynting vector on a surface A, i.e. an overestimation of results using Formula (7).

6.7.1.4 Total power density into the evaluation surface considering reactive near-field effects – $sPD_{\text{mod+}}$

The quantity $sPD_{\text{mod+}}$ is based on the total power density, and considers also the imaginary part of the Poynting vector to account for non-propagating energy transfer in the reactive near-field. It shall be calculated according to Formula (11).

$$sPD(\boldsymbol{r}_0) = \frac{1}{\hat{A}(\boldsymbol{r}_0)} \int_{A(\boldsymbol{r}_0)} \left[\left(\left\| \Re\{\boldsymbol{S}(\boldsymbol{r})\} \right\| \cdot \Xi\left\{\cos^{-1}\left[\boldsymbol{n}_R(\boldsymbol{r}) \cdot \boldsymbol{n}_A(\boldsymbol{r})\right]\right\} \right)^2 + \left(\left\| \Im\{\boldsymbol{S}(\boldsymbol{r})\} \right\| \right)^2 \right]^{1/2} \mathrm{d}\hat{A}(\boldsymbol{r}) \tag{11}$$

$\left\| \Im\{\boldsymbol{S}(\boldsymbol{r})\} \right\|$ is the magnitude of the imaginary part of the complex Poynting vector $\boldsymbol{S}$ at the location $\boldsymbol{r}$

and the other terms are as specified in 6.7.1.3.

NOTE Formula (11) corresponds to magnitude of the Poynting vector (real and imaginary parts) on a surface A, i.e. an overestimation of results using Formula (7) and Formula (8).

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6.7.2 Post-processing procedure

Post processing shall include the following steps:

a) determination of the Poynting vector on the evaluation surface (e.g. using field reconstruction algorithms). Where the plane-wave equivalent approximation is valid (see 7.4.2.1), the power density can be directly computed by measurement of the E-field magnitude or H-field magnitude using the far-field characteristic impedance η_0;

b) determination of the power density from the Poynting vector according to Formula (7), Formula (8), and Formula (11). As example, according to Formula (8), the power density is obtained from the Poynting vector using Formula (12):

$$S_{\text{tot}} = \frac{1}{2}\text{Re}\left\{\left(E_y H_z^* - E_z H_y^*\right)\hat{\mathbf{x}} + \left(E_z H_x^* - E_x H_z^*\right)\hat{\mathbf{y}} + \left(E_x H_y^* - E_y H_x^*\right)\hat{\mathbf{z}}\right\} \tag{12}$$

where

$$\boldsymbol{E} = \left[\text{Re}\left(E_x\right) + \text{j}\text{Im}\left(E_x\right)\right]\hat{\mathbf{x}} + \left[\text{Re}\left(E_y\right) + \text{j}\text{Im}\left(E_y\right)\right]\hat{\mathbf{y}} + \left[\text{Re}\left(E_z\right) + \text{j}\text{Im}\left(E_z\right)\right]\hat{\mathbf{z}}$$

$$\boldsymbol{H} = \left[\text{Re}\left(H_x\right) + \text{j}\text{Im}\left(H_x\right)\right]\hat{\mathbf{x}} + \left[\text{Re}\left(H_y\right) + \text{j}\text{Im}\left(H_y\right)\right]\hat{\mathbf{y}} + \left[\text{Re}\left(H_z\right) + \text{j}\text{Im}\left(H_z\right)\right]\hat{\mathbf{z}}$$

Formula (12) can also be written as shown by Formula (13):

$$S_{\text{tot}} = \sqrt{S_x^2 + S_y^2 + S_z^2} \tag{13}$$

where

$$S_x = \frac{1}{2}\text{Re}\left(E_y H_z^* - E_z H_y^*\right)$$

$$S_y = \frac{1}{2}\text{Re}\left(E_z H_x^* - E_x H_z^*\right)$$

$$S_z = \frac{1}{2}\text{Re}\left(E_x H_y^* - E_y H_x^*\right)$$

c) spatial averaging of the power density over the required averaging area to determine the sPD on the evaluation surface, in accordance with 8.4 of IEC/IEEE 63195-2:2021. The rationale for use of square or circular shapes for power density averaging area in conformity evaluations is provided in Annex D;

NOTE 1 It is possible that applicable national regulations or exposure standards provide a different definition or interpretation for PD.

d) determination of $psPD$, the peak value of the sPD, and any secondary peak spatial-average power density values (secondary peaks).

NOTE 2 Secondary peak measurements are not required if the sPD is determined on the entire evaluation surface.

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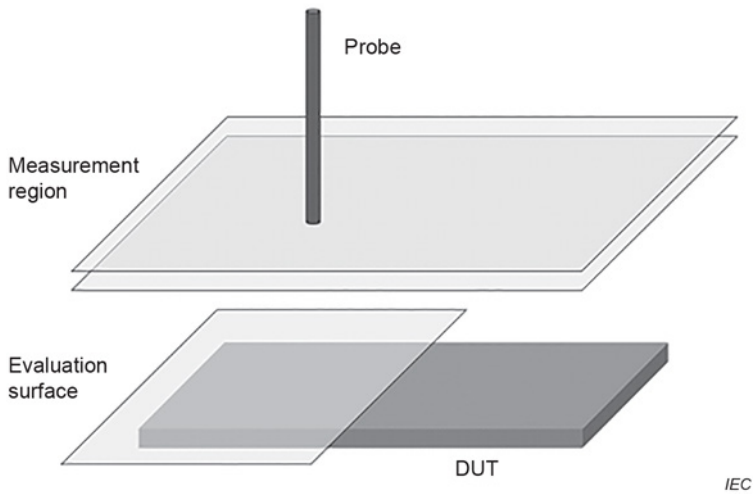
Field reconstruction algorithms may be used to transform the measured fields in the measurement region to the Poynting vector on the evaluation surface (Figure 2) with known uncertainty. This may include intermediate steps such as calculating the H-field from the E-field (or vice versa) or retrieving field components and power densities from the measured data (e.g. the phase from the amplitude). See Annex E for more information on field reconstruction methods.



NOTE The measurement and evaluation surface dimensions, and their orientations and positions, are simplified for illustration purposes (see 7.2.4 for additional information).

Figure 2 – Simplified view of a generic measurement setup involving the use of reconstruction algorithms

6.7.3 Requirements

The following requirements apply to the post-processing.

a) The power density on the entire evaluation surface shall be determined from the field measurements on the measurement region (e.g. using field reconstruction) with sufficient resolution to ensure that the $psPD$ uncertainty is within the value stated by the system manufacturer.

b) The power density shall be determined from the Poynting vector (unless the plane-wave equivalent approximation is valid).

c) The power density shall be spatially averaged over the specified averaging area (e.g. 1 cm^2 and/or 4 cm^2) of the relevant exposure standard or national regulations.

d) The values and locations of the $psPD$ and any secondary peaks shall be recorded. Alternatively, the sPD distribution shall be provided.

e) The uncertainty of the post-processor shall be determined.

f) The limitations for which the uncertainty is valid shall be assessed (e.g. with respect to frequency, measurement region, etc.).

g) The post-processing methods shall be documented by the system manufacturer including uncertainty and limitations.

Conformity with these post-processing requirements shall be documented by the manufacturer of the measurement system.

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7 Protocol for PD assessment

7.1 General

A high-level flow-chart of the evaluation process for power density assessment is shown in Clause 5. Beginning with an evaluation plan and measurement approach, the process converges to the full power density evaluation and uncertainty analysis. Documentation and reporting complete the evaluation process.

NOTE This document does not contain information needed to configure DUTs for specific wireless technologies, including specific settings such as the operating mode or data rate to ensure that the maximum PD is obtained.

7.2 Measurement preparation

7.2.1 Relative system check

A relative system check according to the procedures of Clause A.3 shall be completed before performing PD assessment for a DUT. The relative system check evaluates field probe function, field probe calibration, scanning system, measurement instrumentation and post-processing. The requirements on relative system check are as follows.

a) If the relative system check uses a source that does not have a traceable absolute target value, ensure that an absolute system check has been performed according to Clause A.4, or relative system check target value has been determined after the system validation or after the absolute system check at user site.

b) The relative system check procedure shall be performed on the same PD measurement system used for evaluation of the DUT (see 7.4).

c) The relative system check shall be performed such that all elements of the measurement system are valid for the DUT to be measured (e.g. if the verification is performed at a different frequency than the test frequency bands of the DUT, then the calibration parameters used in the verification shall be valid for the test frequencies).

d) The relative system check shall meet the acceptability criteria in A.3.4.

NOTE 1 Because an absolute system check test fulfils all the requirements, an absolute system check test can also be performed instead of a relative system check.

NOTE 2 In case the system is based on a frequency-continuous sensor model valid over the entire frequency range, it is sufficient to perform the system check at the closest frequency of the verification antennas specified in Annex B. In case the system is based on a narrow frequency calibration, the verification is performed within the centre frequency of the measured DUT band ± 15 %.

7.2.2 DUT requirements

The requirements of the DUT are as follows.

a) The antenna(s), battery and accessories shall be those specified in the user manual. If this information is not available in the user manual, DUT should be equivalent to production line samples to be sold on the market. Accessories that have been approved for use with the DUT by the device manufacturer shall also be considered (e.g. additional accessories that are available on the manufacturer's website that have been approved for use with the DUT). They shall be documented in the measurement report.

b) All antennas, their location and size, including arrays and sub-arrays, shall be identified.

c) The battery shall be fully charged before each measurement and no external connections or cables affecting the result shall be used.

   A lower battery level, not less than 60 %, is allowed provided it is demonstrated that the power level has not dropped by more than the DUT drift uncertainty.

d) When national regulatory agencies allow tests to be performed on prototypes, verification shall be undertaken by the device manufacturer to ensure the commercial version has the exact same mechanical, electrical, and operating characteristics as the tested prototype. Where this cannot be guaranteed, testing shall be repeated by sampling of unmodified commercial product versions.

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e) Accessories that can affect the RF output power or RF current distribution of the DUT shall be tested according to the intended use conditions.

f) Transmitters operating, for example, below 6 GHz can influence the PD of the transmitters due to coupling with the probe, etc., and such influences shall be taken into account. If the coupling from other active transmitters cannot be filtered out (e.g. frequency-selective measurement system), other transmitters shall be inactive during the measurement.

7.2.3 DUT preparation

The following requirements apply when preparing the DUT for testing.

a) The RF output power and frequency (channel) shall be controlled either by a wireless link or test mode software (active mode). Alternatively, an external generator or a synthesiser and amplifier may be used to replace the transmitter (passive mode), provided that both the measured fields and the power density assessment of the DUT are unaffected, and the impact on power density assessment uncertainty is properly evaluated and remains acceptable. The power chains to all transmitting elements of the antenna array(s) shall be evaluated to accurately determine the input power fed to the antenna.

NOTE 1 National regulations can exist regarding the use of an external generator or a synthesiser and amplifier in place of the transmitter.

NOTE 2 In practice it can be difficult to use external signal generators, etc., to replace a DUT and have the same field distribution.

b) When beamforming is supported by the device, the beam shall be fixed for the duration of the PD evaluation, to facilitate consistent results.

c) Record the maximum time-averaged output power of the DUT for each tested frequency band and operating mode. If power scaling is obtained using call handling (see 7.4.3.2), record the time-averaged output powers of N_c channels as specified in 7.4.3.3 for each tested frequency band.

NOTE 2 The maximum time-averaged power of the DUT can be verified, e.g. if applicable, by conducted power measurements with a fully charged battery or, according to radiated power measurements and other operating parameters to support the scaling.

d) If performing measurement of simultaneous transmission of uncorrelated or Type 2 correlated signals (see 7.5), establish the maximum output power for each transmitter and antenna as described in step a) to ensure the aggregate transmit power from all antennas is also at the maximum.

e) If the DUT is capable of controlling its transmit power over time to maintain the time-average power density below the applicable limit, the time period averaging procedure in IEC/IEEE 62209-1528:2020 may be applied. If the frequency and relative phase between transmitting elements is kept constant, it is sufficient to measure the amplitude of the E-field, H-field, or Poynting vector at a fixed location. Otherwise the power density shall be measured at the evaluation surfaces. The relevant time-averaging period or periods is/are specified in accordance with international guidelines (e.g. ICNIRP [2]) or national regulations. The time-averaging test procedure in IEC/IEEE 62209-1528:2020 only applies to devices that have network-independent capability to control transmission power over specific durations and intervals.

NOTE 3 Some regulatory authorities can have other or different requirements for PD measurements of devices supporting power control and time averaging.

f) Record whether proximity sensors are used to lower the output power and the DUT positions and operating modes where proximity sensor activation applies. Verify whether the proximity sensor activation or deactivation is affected by the measurement system. In case the proximity sensor system is affected, either the proximity sensor shall be forced into activation or deactivation mode using test software, as appropriate, or when possible the measurement shall be taken in a separation distance at which the proximity system is not affected. The procedures of 7.7 in IEC/IEEE 62209-1528:2020 may be used to determine the proximity sensor triggering distances. If the proximity sensor performs or triggers time period averaging, the proximity sensor procedure in IEC/IEEE 62209-1528:2020 may be applied with time period averaging deactivated.

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7.2.4 Selecting evaluation surfaces

7.2.4.1 General

The device manufacturer shall indicate all device positions that are applicable for the DUT (e.g. via user manual). National regulatory requirements also exist. The locations and orientations of the evaluation surfaces shall be determined based on the specified device positions and usage.

The shape of the evaluation surface depends on the exposed region of the body. 7.2.4.2 specifies the flat evaluation surface to be used for evaluating exposure in the torso or other locally flat regions of the body. 7.2.4.3 specifies the SAM surface for PD evaluations when the device is evaluated in voice-mode at the ear. If the SAM surface for PD or flat evaluation surfaces are not applicable, 7.2.4.5 specifies specific evaluation surfaces to be used.

Projection of the measured fields onto any non-planar evaluation surface shall be carried out applying the procedure of 8.3 of IEC/IEEE 63195-2:2021. This involves constructing surfaces around each centre point. The surface has an area that is the intersection of the evaluation surface with a sphere of radius $r_T = \sqrt{A/\pi}$. Triangulation algorithms are used to divide the non-planar evaluation surface into a set of triangles, and the step-by-step procedure in 8.3 of IEC/IEEE 63195-2:2021 is applied.

7.2.4.2 Body-worn evaluation surfaces

The evaluation surface is flat for exposure of the torso or other locally flat regions of the body. The shape and extent of the evaluation surface corresponds to the inner surface of the virtual flat phantoms including elliptical flat phantom described in IEC/IEEE 62209-1528:2020.

The evaluation distance (distance from DUT to evaluation surface) is the separation distance (distance from DUT to the outer surface of the virtual phantom) plus the 2 mm shell thickness. This enables total exposure ratio (TER) evaluations at the same surfaces as described in 7.5.

NOTE Touch would be 2 mm from the surface of the device. However, some regulators can also directly specify the evaluation distance including the shell, i.e. 2 mm. This needs to be clarified prior to doing testing.

When performing measurements for body-worn exposure, the separation distance shall be set according to the following three hierarchical options:

a) Regulatory requirement

   If there is a regional, territorial or country-specific regulatory requirement which specifies the DUT separation distance, the DUT shall be positioned according to this requirement.

b) "Intended use distance" specified by the manufacturer

   If there is no regulatory requirement, then the intended use condition or separation distance specified by the manufacturer shall be used. This information shall be acquired from the user documentation that accompanies the DUT.

c) Default separation distance

   If neither of the previous options are applicable, then the DUT shall be measured with each accessible face at 0 mm separation distance.

7.2.4.3 Held at ear evaluation surfaces

If the device is intended to be held on the ear during voice calls (voice-mode, including e.g. VoIP mode), four evaluation surfaces shall be tested, corresponding to the cheek and tilt positions on the left and right sides of the head as specified in IEC/IEEE 62209-1528:2020.

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The basis of the virtual evaluation surfaces is the inner surface of the SAM phantom described in IEC/IEEE 62209-1528:2020. The geometric parameters of the SAM phantom are based on anthropometric data from Gordon et al. [11]. The rationale for the SAM shape for SAR is provided in IEC/IEEE 62209-1528:2020.

The only modification to the SAM phantom for PD evaluation is the pinna; i.e. at the pinna, the inner surface of the SAM phantom is modified from that described in IEC/IEEE 62209-1528:2020. The inner surface is 2 mm from the outer surface of the SAM phantom at all points. Figure 3 and Figure 4 show the SAM head surface for SAR evaluations and the SAM surface for PD evaluations, respectively.

The tilt positions may be excluded if it can be demonstrated for any phase and amplitude configuration that the exposures in the tilt positions are likely to be more than 3 dB below the exposure in the corresponding cheek positions. Supporting information shall be provided in the test report (i.e. based on the location of the antenna array on the DUT).

NOTE 1 The exposure of the pinna is directly evaluated in this document as applicable guidelines do not distinguish between body and extremities above 6 GHz.

NOTE 2 IEC/IEEE 62209-1528:2020 has further information on statistical approaches to support the elimination of the tilt position for SAR.

NOTE 3 Research on conservativeness of this choice of evaluation surfaces for PD will be considered for future amendment of this document.

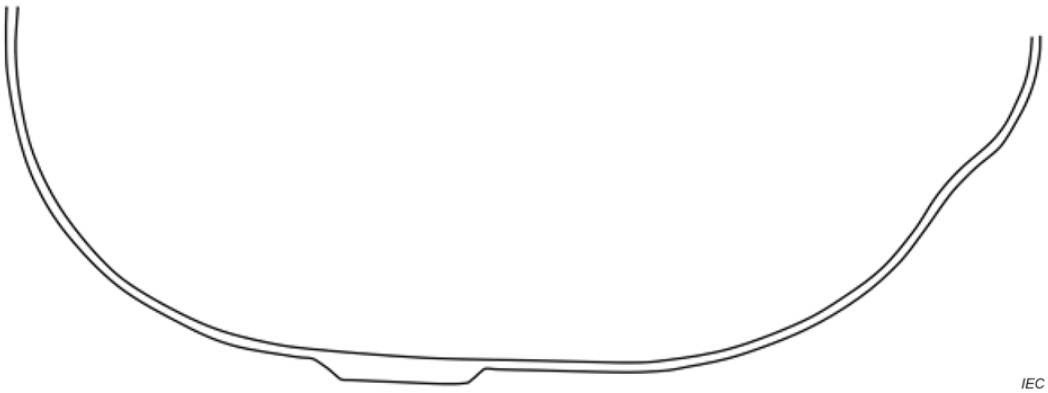

Figure 3 – Cross-sectional view of SAM phantom for SAR evaluations at the reference plane, as described in IEC/IEEE 62209-1528:2020

Figure 4 – Cross-sectional view of SAM virtual phantom for PD evaluations at the reference plane (shell thickness is 2 mm everywhere, including at the pinna)

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7.2.4.4 Evaluation surfaces when held at other locations of the head

If the intended use is at other locations of the head, such as the front of the face or top of the head, the DUT position and the evaluation surface shall be described in the test report. The position of the evaluation surface shall always be chosen in such a way that a conservative estimate assessment with respect to the distance between the DUT and the head of the user results.

A simple option is to use the body-worn evaluation surface (7.2.4.2) for side(s) of the DUT intended to be held at the head, using the default evaluation distance (7.2.4.2 c)).

NOTE Research on conservativeness of this choice of evaluation surface will be considered for future amendment of this document.

7.2.4.5 Specific evaluation surfaces

Device specific evaluation surfaces other than those specified in 7.2.4.2 and 7.2.4.3 shall be used if the flat surface or SAM surface does not allow a conservative estimate of the exposure and the device is intended for operation on other parts of the body than the head or torso.

Exposure of the hands or limbs shall be considered in the case of hand-held or limb-worn devices (e.g. mobile phones, small hand-held phablets) at appropriate separation distances. Until representative surface is developed and introduced in this document, body-worn evaluation surface can be considered for this purpose.

NOTE The vast majority of the time, appropriate separation distance for hands or limbs will be at touch position. When a different separation distance is used, a rationale is provided in the test report and to the regulators to support the request.

Examples of device specific evaluation surfaces (i.e. inner surfaces of specific phantoms) are described in IEC/IEEE 62209-1528:2020. Justification for the use of specific evaluation surfaces shall be documented in the test report. Alternative device positioning procedures may also be required.

7.2.4.6 Coordinate system for DUT positioning

Coordinate systems for the acoustic reference points and vertical and horizontal centre lines of DUT (see Figure 6) facilitate the accurate positioning and orientation of the evaluation surface on the virtual phantom. Reference points and axes on the DUT shall be specified based on the shape and size of the DUT. The scanning system shall correlate these points so that the evaluation surfaces on the phantom can be correctly aligned to the DUT.

The offset and rotation between these reference coordinate systems can be used to provide an unambiguous description of device position relative to the evaluation surface. A definition of the coordinate system for the left ear reference point (ERP) is illustrated in Figure 5.

The x-, y- and z-axes shall form a right-handed coordinate system. For the left ERP, the axes are specified as follows.

a) The z-axis is specified by a connecting line between the left and the right ERPs, and points from the right to the left from the point of view of the virtual phantom. The z = 0 origin is at the left ERP.

b) The y-axis lies in the reference plane along the back-to-mouth (B-M) line and is perpendicular to the z-axis.

c) The x-axis is perpendicular to the reference plane along the neck-to-front (N-F) line and cuts the reference plane at the left ear reference point.

For the right ERP, the reference coordinate system can be specified analogously. A definition of a DUT reference points and axes are shown in Figure 6.

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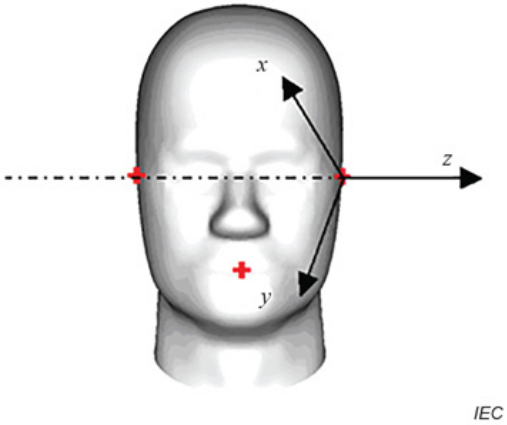
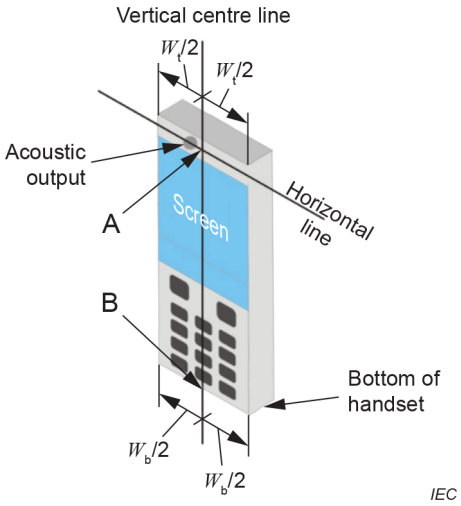
For the flat phantom, the x-axis and y-axis are parallel to the virtual flat phantom shell and the z-axis is perpendicular to it.



Key

x, y, z Axes of the coordinate system relative to the virtual SAM phantom

Figure 5 – Example reference coordinate system for the left-ear ERP of the SAM phantom



Key

w_t Width of the handset at the level of the acoustic output

w_b Width of the bottom of the handset

A Midpoint of the width w_t of the handset at the level of the acoustic output

B Midpoint of the width w_b of the bottom of the handset

Figure 6 – Example reference points and vertical and horizontal lines on a DUT

7.3 Tests to be performed

7.3.1 General

The total exposure from the DUT is determined from power density evaluations and exposure combining using the following steps (see also Figure 7).

1) Select a frequency band of the DUT (see 7.2.3).

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2) Select a measurement region for the frequency band of step 1) that allows power density to be determined on evaluation surface(s) based on the specified DUT positions (see 7.2.4).

3) Identify all the antenna configurations of the DUT for the measurement region of step 2). For Type 1 correlated signals (see 7.5) that includes all applicable phase and amplitude combinations of an array or sub-array. When a codebook defining the amplitude and phase combinations is known, apply the codebook.

4) Evaluate the maximum exposure cases among the antenna configurations identified in step 3). Any of the following approaches may be used (see also Annex C of IEC/IEEE 63195-2:2021 for maximum-exposure evaluation techniques, which also need to be validated and documented following the procedure of Annex H of IEC/IEEE 63195-2:2021).

   a) Exhaustive search by measurements: If the number of antenna configurations can be practically applied, measure all antenna configurations. For each measurement, apply the procedure of 7.4. Choose the configuration with the highest $psPD$.

   b) Optimization strategy by measurements: Use an optimization strategy based on measurements of a sufficient subset of antenna configurations allowing to evaluate all configurations (see 7.3.3). For each measurement, apply the procedure of 7.4. The optimization strategy shall determine an upper bound of the $psPD$ and the maximum error (e.g. see Reboux et al. [12], Teniou et al. [13]).

   c) Exhaustive search by simulations: Perform numerical simulations for all antenna configurations identified in step 3) to determine the test configuration with highest $psPD$. See 7.3.2 for details on the simulation approach and model validation against measurements. The $psPD$ for the test configuration with highest $psPD$, and other configurations as described in 7.3.2, shall be measured.

   d) Optimization strategy by simulations: Use an optimization strategy based on numerical simulations of all independent antennas to determine the test configuration with highest $psPD$. See 7.3.2 for details on the simulation approach and model validation against measurements. The $psPD$ for the test configuration with highest $psPD$, and other configurations as described in 7.3.2, shall be measured.

   For the configuration with the highest $psPD$, record the $psPD$, and the sPD distribution or any secondary peaks.

5) Go back to step 3) until all antenna configurations (e.g. sub-arrays) have been tested.

6) Go back to step 2) until all evaluation surfaces have been tested.

7) Go back to step 1) until all frequency bands have been evaluated.

8) Determine the total exposure ratio (TER) including summation of exposures from any simultaneous transmission modes (see 7.5).

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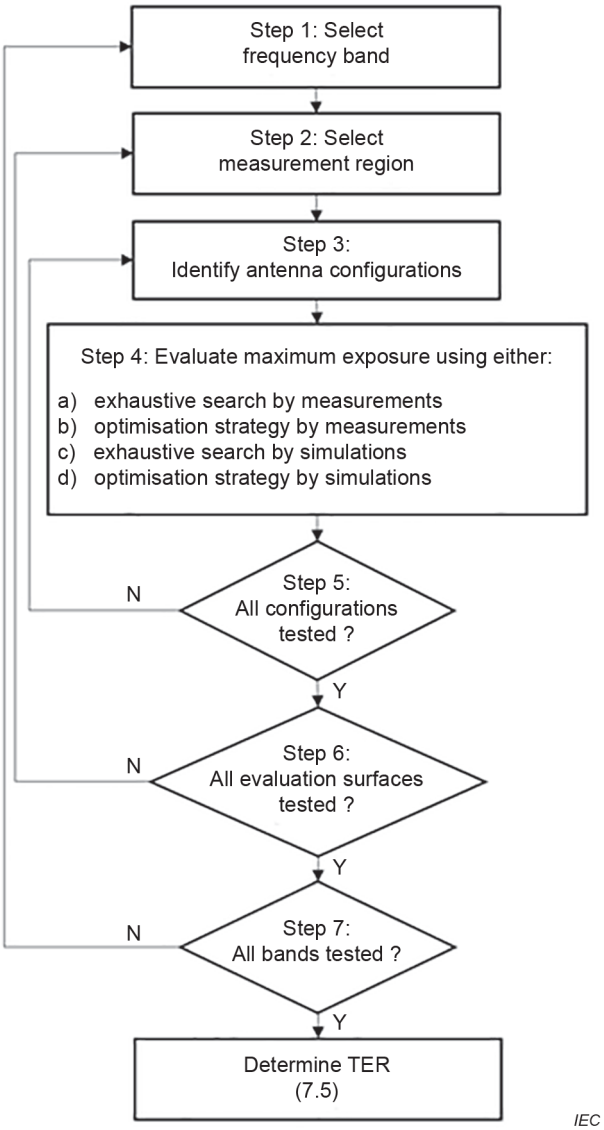

Figure 7 – Flow chart for test procedure in 7.3

7.3.2 Tests to be performed when supported by simulations of the antenna array

A numerical modelling assessment of the DUT may be used to determine the maximum exposure cases among a set of amplitude and phase combinations, as described in IEC/IEEE 63195-2:2021.

The numerical DUT model shall be validated (in accordance with 7.5 of IEC/IEEE 63195-2:2021) to make sure that the numerical predicted configuration resulting in maximum exposure is indeed conservative for the evaluated transmitters. This implies that configurations of the antenna array or antenna sub-array including amplitude and phase information are known and controllable for the measurements in order to validate the relative numerical DUT model.

The procedure has the following steps.

a) At the given frequency band, and measurement region determined from 7.3.1., identify the highest simulated $psPD$, denoted $psPD_{\text{sim,max}}$, from all the simulated $psPD$ results, denoted $psPD_{\text{sim},i}$, where i = 1 to N amplitude and phase combinations.

b) At the given maximum test configuration identified from step a) measure the power density, denoted $psPD_{\text{meas,max}}$.

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c) Measure the power density for all test configurations where the condition of Formula (14) is met.

$$psPD_{\text{sim},i} > psPD_{\text{sim,max}} \times \left(B_{\text{sim}} - \sqrt{B_{\text{sim}}^2 - 1} \right) \tag{14}$$

where

$$B_{\text{sim}} = \frac{1}{1 - \left(1{,}64 U_{\text{sim,rel}}\right)^2} \tag{15}$$

$U_{\text{sim,rel}}$ in Formula (15) is the relative uncertainty (k = 1) of the simulation tool, at the given frequency band, and with the measurement region determined in accordance with 7.3.1.

NOTE 1 The relative uncertainty $U_{\text{sim,rel}}$ is the uncertainty of the simulation with the absolute amplitude uncertainty reduced to relative amplitude uncertainty for the independent antenna elements while the absolute phase uncertainty is still considered. See Clause 9 of IEC/IEEE 63195-2:2021 for uncertainty evaluation of the simulations.

NOTE 2 As an example, for a simulation tool having a relative uncertainty (k = 1) of 10 %, all simulated antenna configurations exceeding 80 % of the maximum measured $psPD$ will be repeated using full power density.

d) Measure the power density for all test configurations where the condition of Formula (16) is met, if not already done.

$$psPD_{\text{sim,scaled},i} > psPD_{\text{limit}} \times \left(B_{\text{sim}} - \sqrt{B_{\text{sim}}^2 - 1} \right) \tag{16}$$

where $psPD_{\text{sim,scaled},i}$ is a simulated result scaled by maximum value of the ratio $psPD_{\text{meas},i} / psPD_{\text{sim},i}$.

e) Verify that all measured and simulated $psPD$ performed at the same frequency band, measurement region, and antenna configuration are within the combined uncertainty (k = 2) of simulation and measurement as given by Formula (17).

$$E_{\text{n}} = \sqrt{\frac{\left(psPD_{\text{sim,scaled},i} - psPD_{\text{meas},i}\right)^2}{\left(psPD_{\text{sim,scaled},i} \times U_{\text{sim}\,(k=2)}\right)^2 + \left(psPD_{\text{meas},i} \times U_{\text{sys}\,(k=2)}\right)^2}} \leq 1 \tag{17}$$

where

E_{n} is the normalized error;

U_{sim} is the expanded uncertainty (k = 2) of the simulation code, at the given frequency band, and measurement region determined from 7.3.1. See Clause 9 of IEC/IEEE 63195-2:2021 for uncertainty evaluation of the simulations;

U_{sys} is the expanded uncertainty (k = 2) of the measurement system, at the given frequency band, and measurement region determined from 7.3.1.

The errors should be combined by RSS in the transformation that corresponds most closely to a Gaussian distribution. Because most of the errors are log-normal distributed, the combined uncertainty should be computed as RSS in decibel (dB). Examples are given in Newell [14], and ETSI ETR 028 [15].

f) If E_{n} > 1, then the measurement procedure of 7.3.3 shall be applied for all configurations with measured result within relative uncertainty of the measurement system from the limit.

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7.3.3 Tests to be performed by measurements of the antenna array

The conservative power density exposure can also be assessed by measurements only using phase recovering techniques combined with optimization techniques (Reboux et al. [12]).

This technique limits the number of required measurements to the number of independent configurations of the antenna array or antenna sub-array. If necessary, the determined maximum configuration can be remeasured, or the conservative maximum value can be used for conformity.

NOTE The number of sufficient independent configurations depends on the optimization technique used; see Annex C of IEC/IEEE 63195-2:2021 for maximum-exposure evaluation techniques.

7.4 Measurement procedure

7.4.1 General measurement procedure

The measurement system shall conform to the requirements of Clause 6. The general measurement procedure is as follows.

It is recommended to apply this measurement procedure using the operating mode and channel having the maximum available output power, to avoid excessive scaling in step f) and to facilitate good signal to noise ratio.

a) First reference: Measure the local E-field or H-field at a point within the measurement region and where the field is within 3 dB of the maximum value or at least 20 dB above the noise level. This reference level will be used to assess output DUT drift during the measurement (see 7.4.4).

   NOTE 1 If the location of maximum field value or a location of at least 20 dB above the noise level is not known, a pre-scan can be used to find such a location. No requirements on the size, resolution, or number of points in the pre-scan are needed, because the pre-scan is only used to find a suitable point for reference measurements.

b) Field scan: Measure the fields over the measurement region as described in 7.4.2. Different measurement techniques are applied depending on the measurement system and whether the evaluation surface is in the far-field. The scan shall conform to the requirements of 6.5.

   NOTE 2 The scan can include a combination of methods to reduce the measurement time, as long as this does not increase the measurement uncertainty. One example is to first perform a scan while the probe is continuously moving over the measurement region, then measure discrete points in a sub-region where the fields are at least −17 dB of the applicable exposure limit.

c) Check that the peak is captured: Calculate the sPD on the evaluation surface from the fields in step b) and ensure that the $psPD$ is accurately evaluated. The averaging area A_{av} for the calculation of $psPD$ is specified by the applicable exposure limits or regulatory requirements. Two checks shall be performed.

   The first check is to ensure that sufficiently large region has been measured and the $psPD$ is not on the boundary of the evaluation surface. The extent of the scan area shall be such that the highest truncation level of the E-field or H-field shall be lower than the specification of the manufacturer for meeting the specified reconstruction uncertainty.

   NOTE 3 The check that the $psPD$ is on the boundary only applies if the evaluation surface is a sub-region of the virtual phantom. If the evaluation surface is the full virtual phantom, then expanding the measurement region will not change the location of the $psPD$.

   The second check is to ensure that that the field reconstruction is not impacted by the measurement region size and therefore has no influence on the $psPD$ result. This can be tested by checking convergence of the two $psPD$ results. Calculate a second $psPD$ value using a subset of values from the existing measured data (e.g. having all results from edges of the measurement region removed). The difference between these two $psPD$ values shall be within the uncertainty of the measurement area truncation (TR, see 8.4.15). If the reconstruction technique is not used, this second check can be omitted;

   If either of these checks fails, expand the measurement region and go back to step b).

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